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(52) UK CL (Edition K)
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(58) Field of search
UK CL (Edition K) H1C CA CBAA CBAX CCX CF CG CH CS
INT CL[5] H01S

(54) **A semiconductor-laser-pumped, solid-state laser**

(57) A laser comprises a semiconductor pumping laser 1, a solid-state laser medium 3 laser medium 3 being plate shaped having a thickness less than, or for example of circular cross-section (e.g. Fig. 12) with a diameter less than, the broadening width of the pumping light in the solid-state laser medium 3, laser 1 being arranged close to the face of the laser medium. Reflecting film 42 is provided on base block 41 and such a film may also be on the upper surface of laser medium 3. A lens may be provided on the input facet of laser medium 3 (Fig. 6), or lenses (8, 9) (Fig. 10) utilised. (Fig. 2) includes a waveguide resonator. The laser may be side-pumped, and a plurality of pumping lasers may be used (Figs. 4, 5, 7, 8 and Fig. 16). The resonator may be one dimensional unstable (Figs. 8, 16). Further embodiments (Figs. 9-16) comprise laser medium (3) in a holding substance (105). Various laser medium (3) cross-sections are disclosed (e.g. Figs. 12-14). Laser medium (3) may be on a metal block (5) (Figs. 17-20) and in a container (8), or may be between metal blocks (Figs. 21, 22).

FIG. 1

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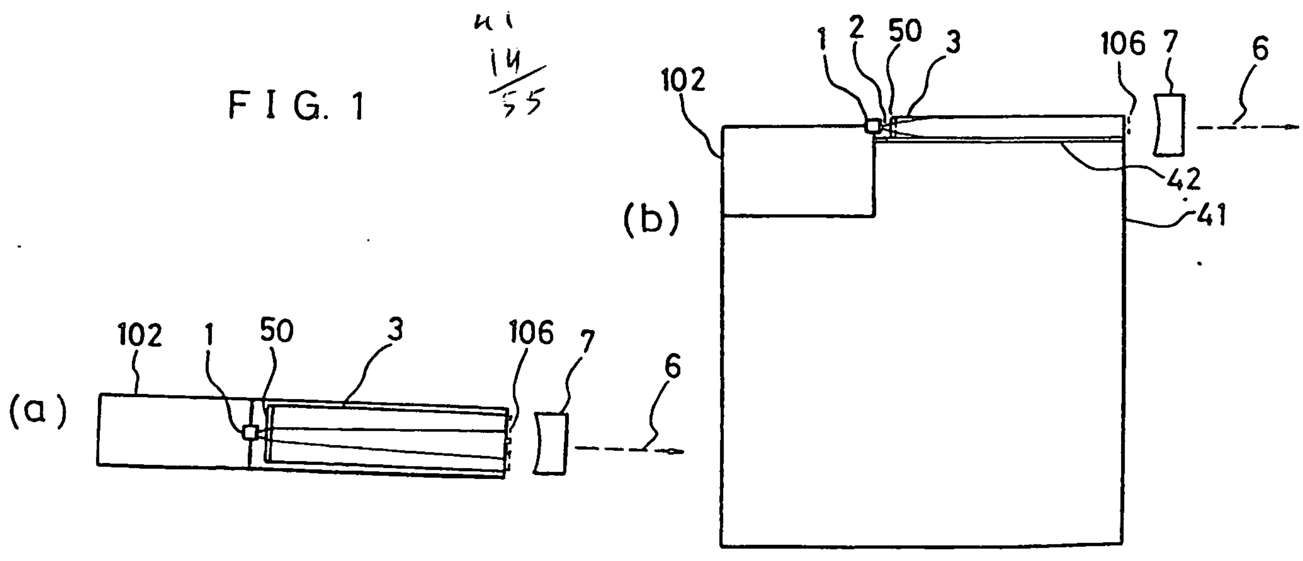

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FIG. 1

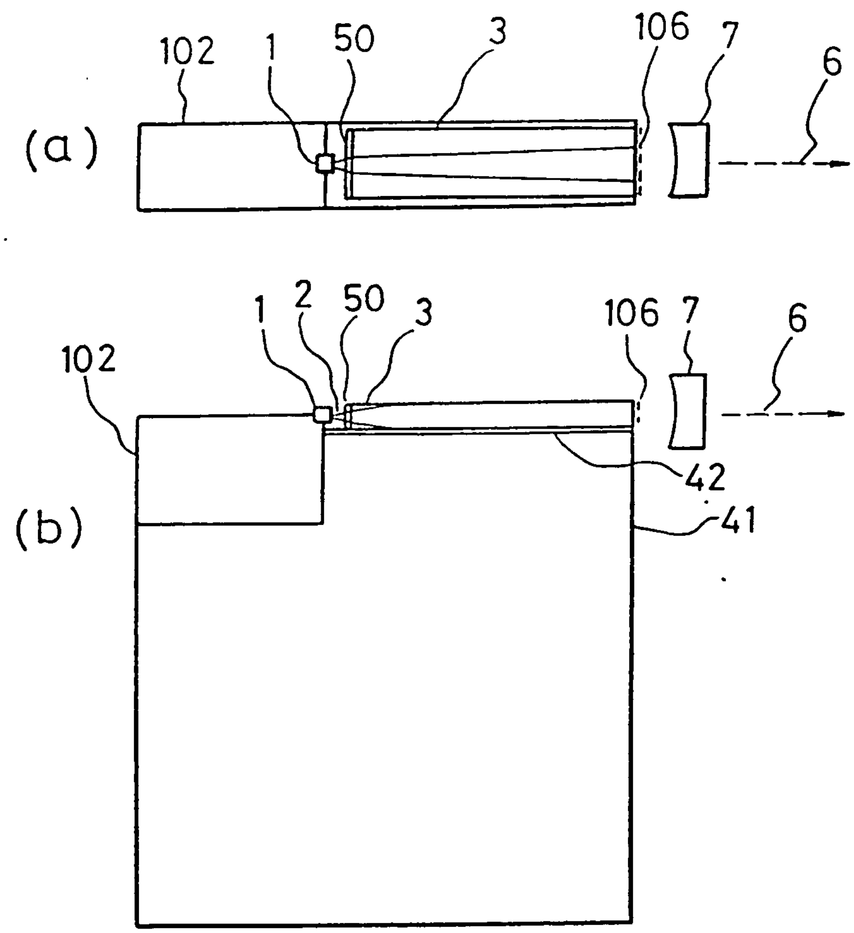


FIG. 2

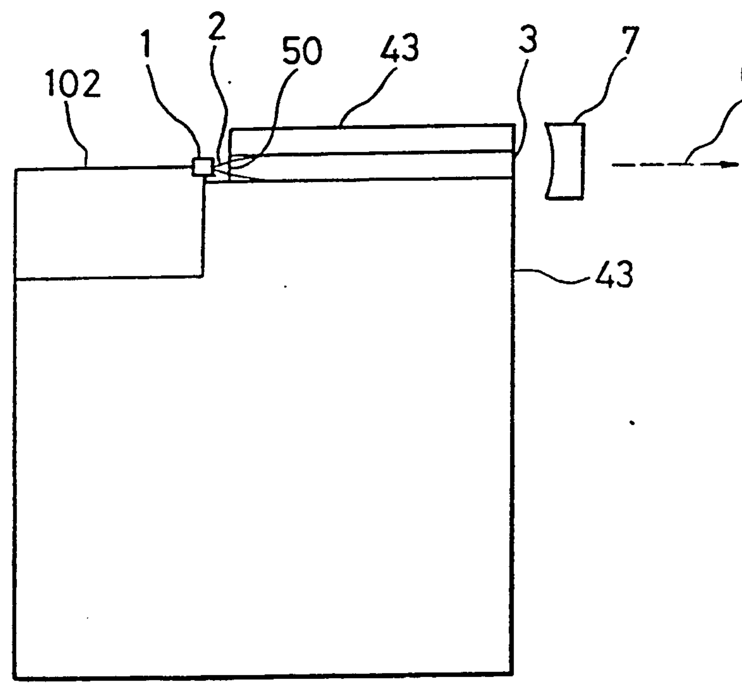


FIG. 3

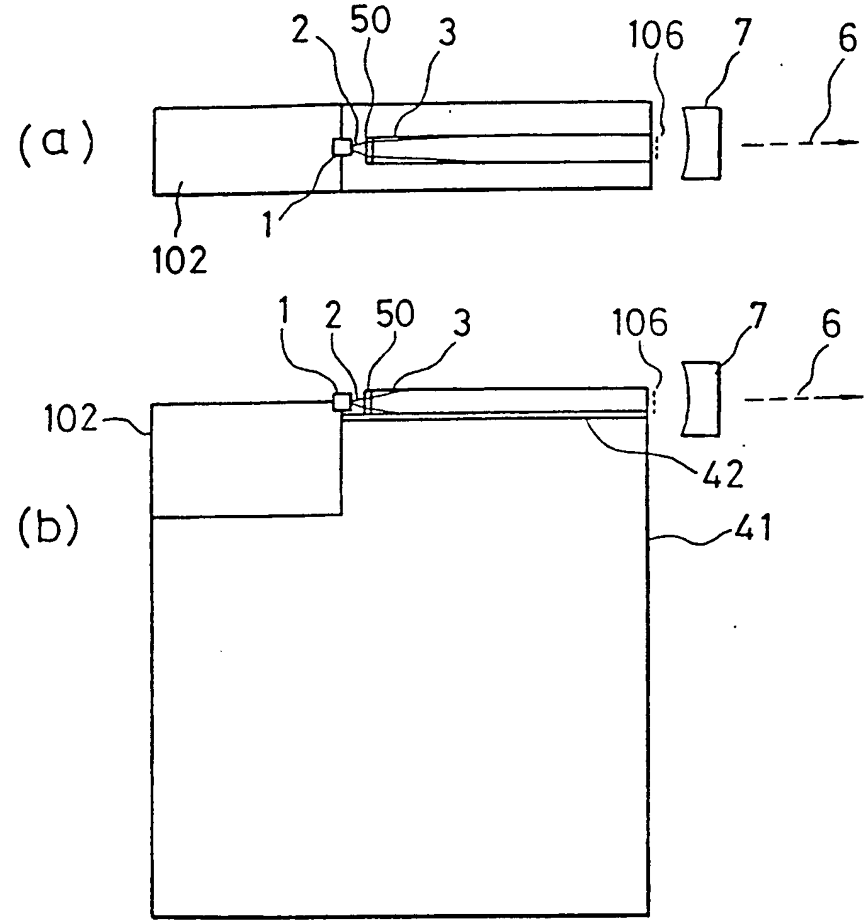

(a)
2
50
3
106
7
6
1
102
(b)
1
2
50
3
106
7
6
102
42
41

FIG. 4

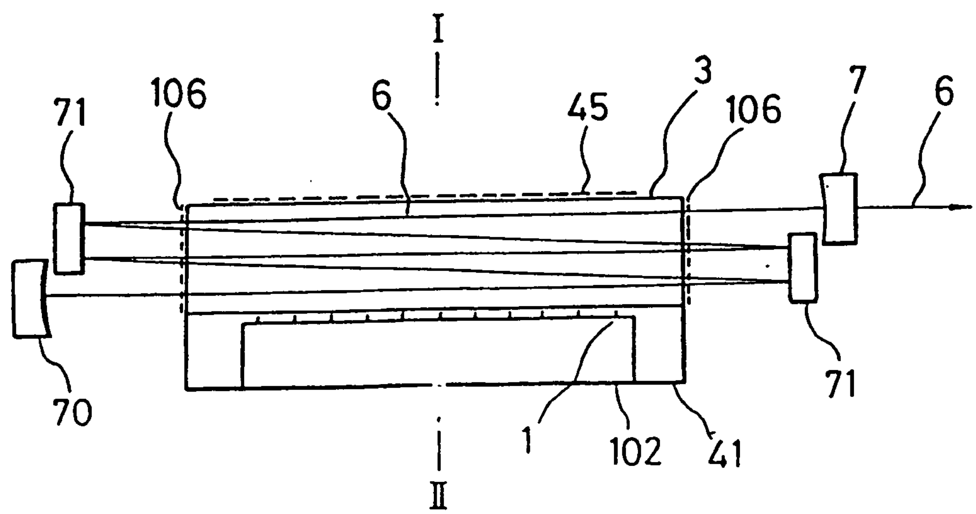

I
71
106
6
45
3
106
7
6
70
1
102
41
71
II

FIG. 5

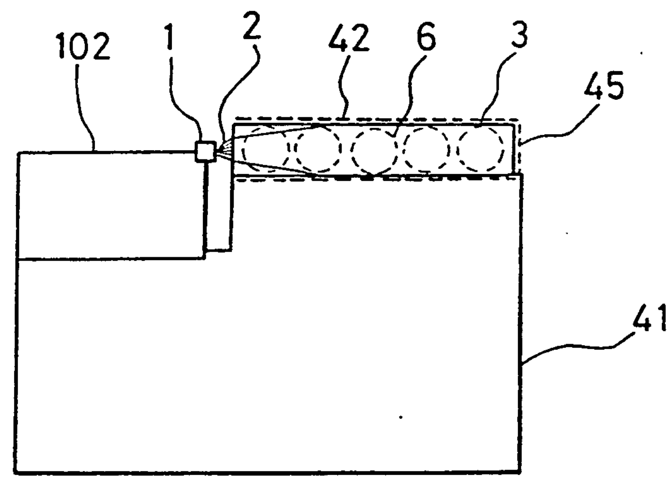


FIG. 6

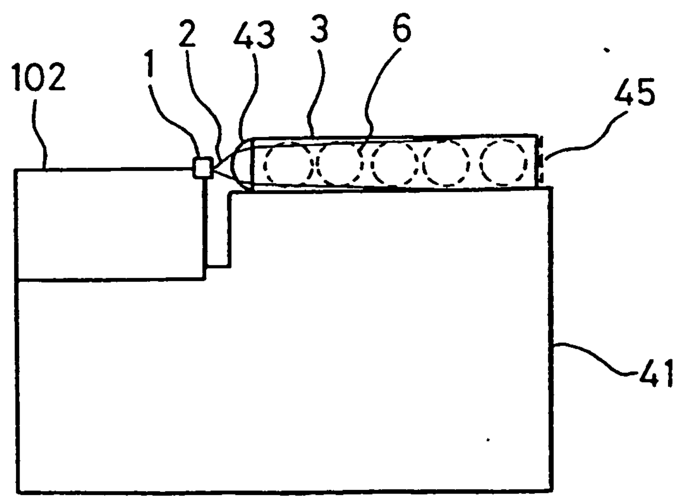


FIG. 7

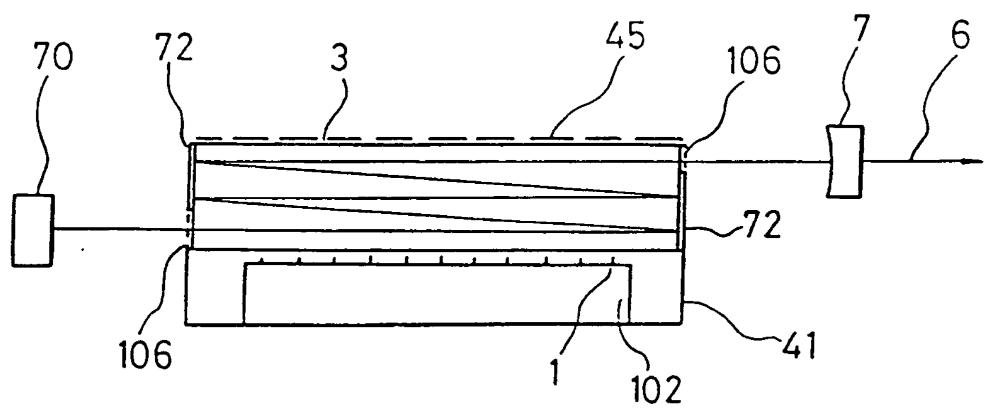


FIG. 8

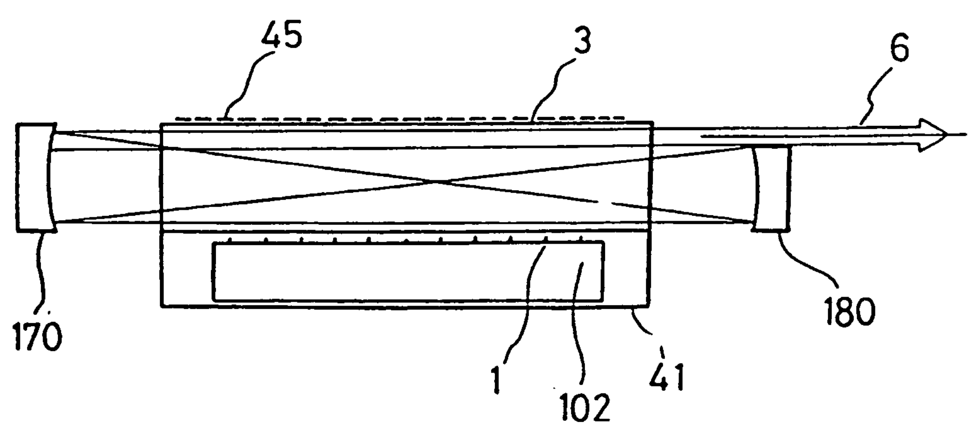


FIG. 9

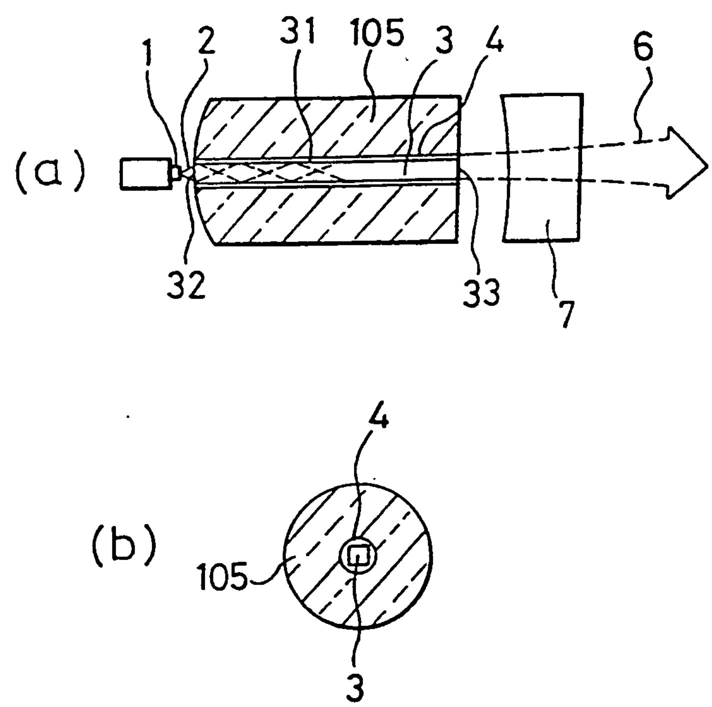


FIG. 10

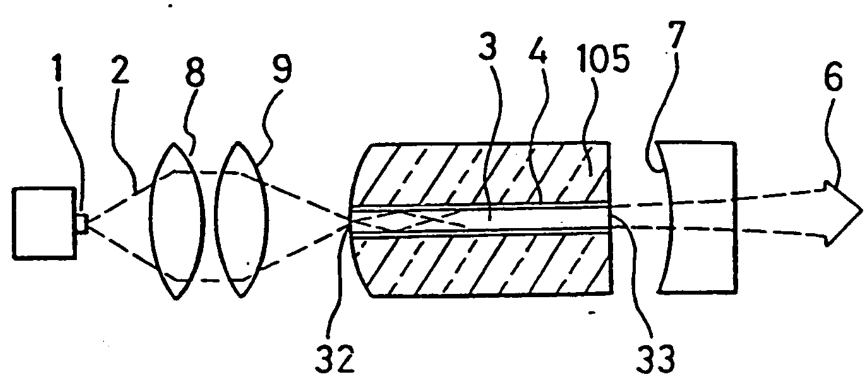


FIG.11

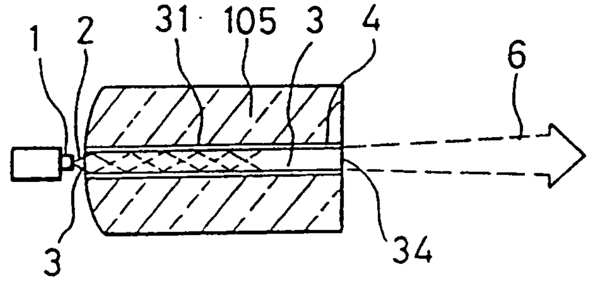


FIG.12

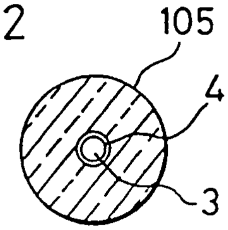


FIG.13

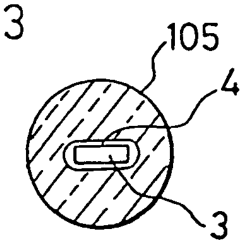


FIG.14

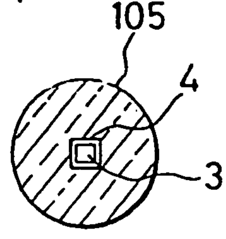


FIG. 15

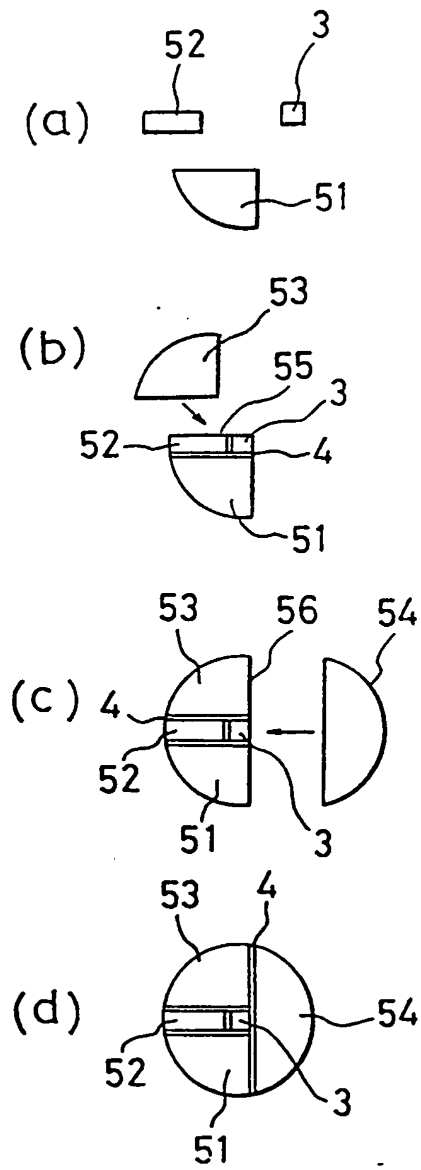


FIG. 16

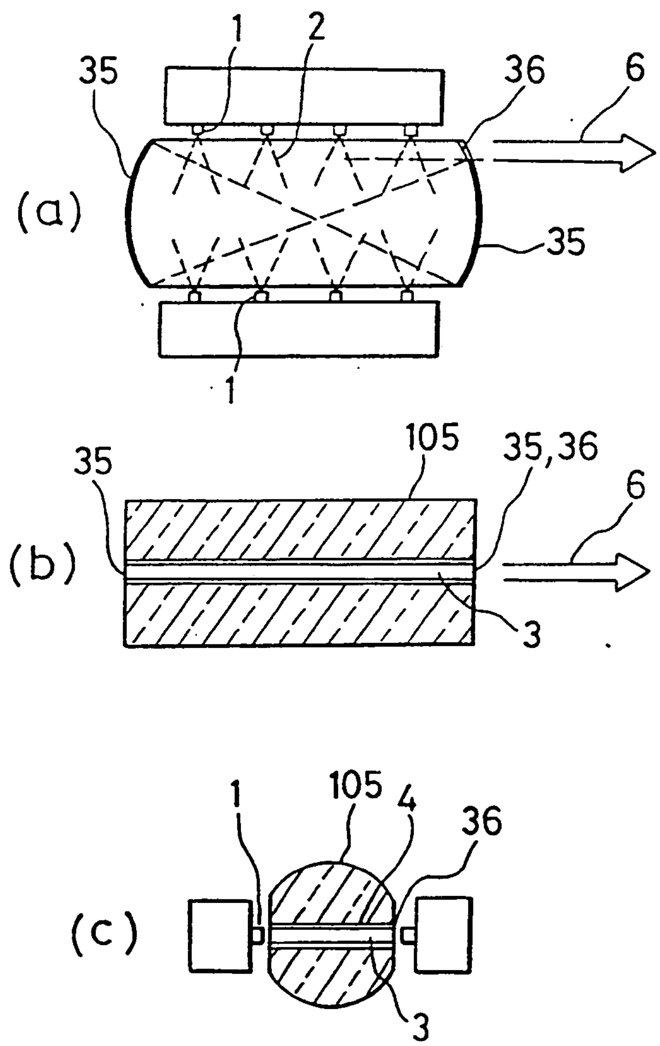


FIG. 17

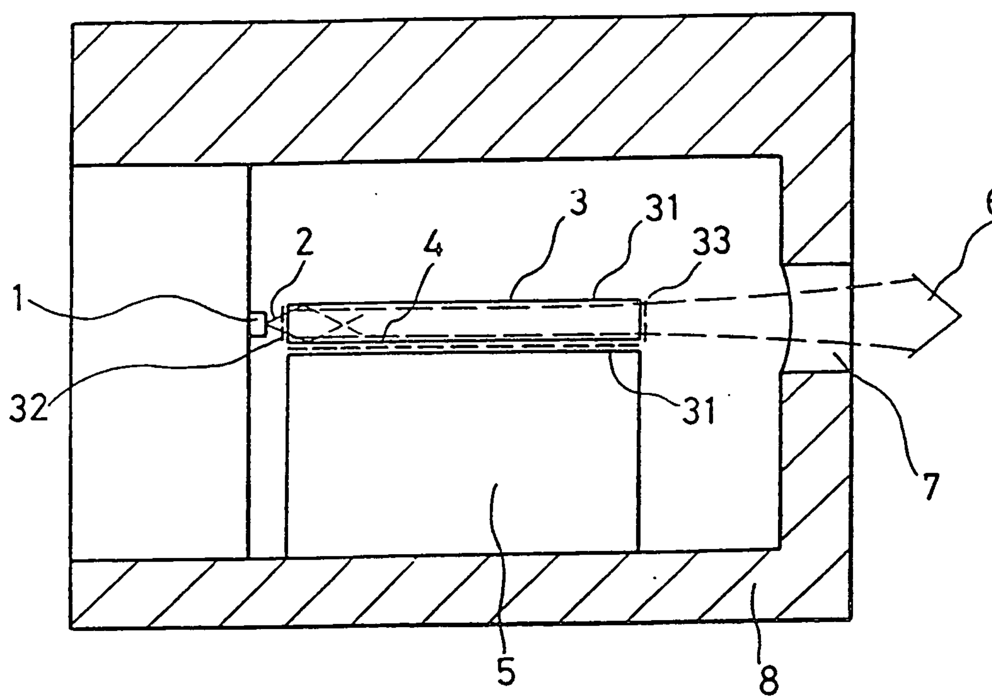


FIG. 18

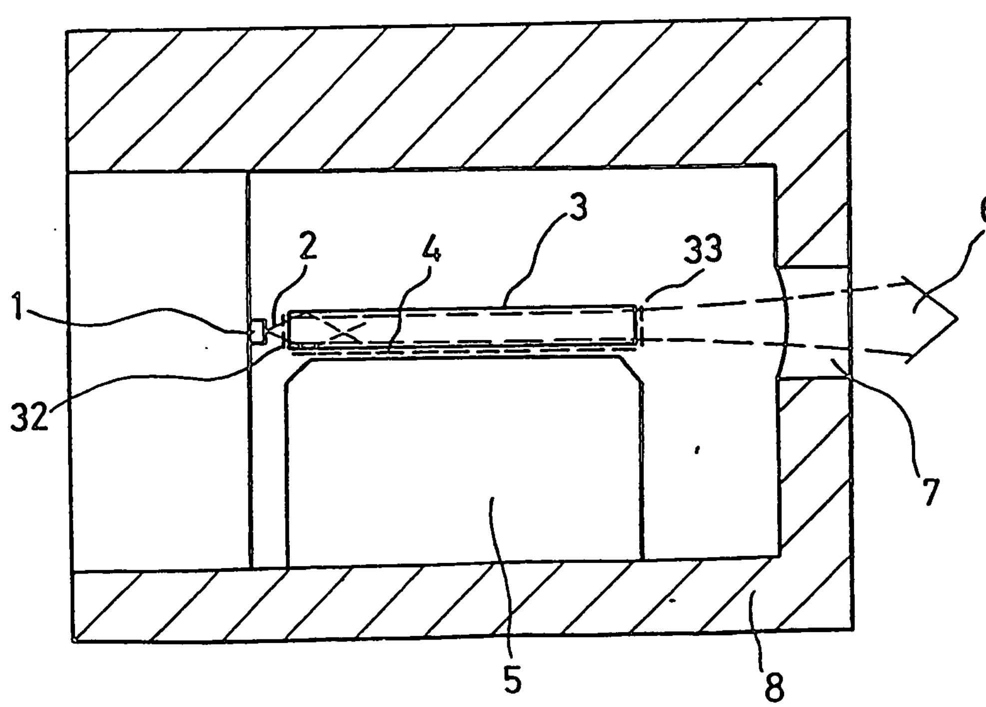


FIG. 19

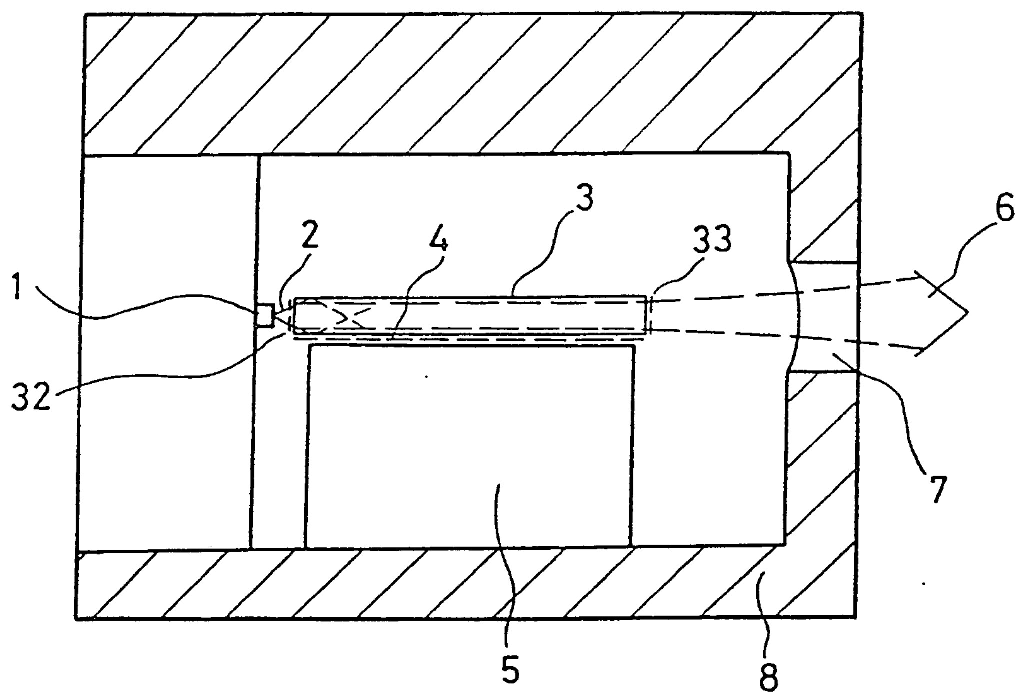


FIG. 20

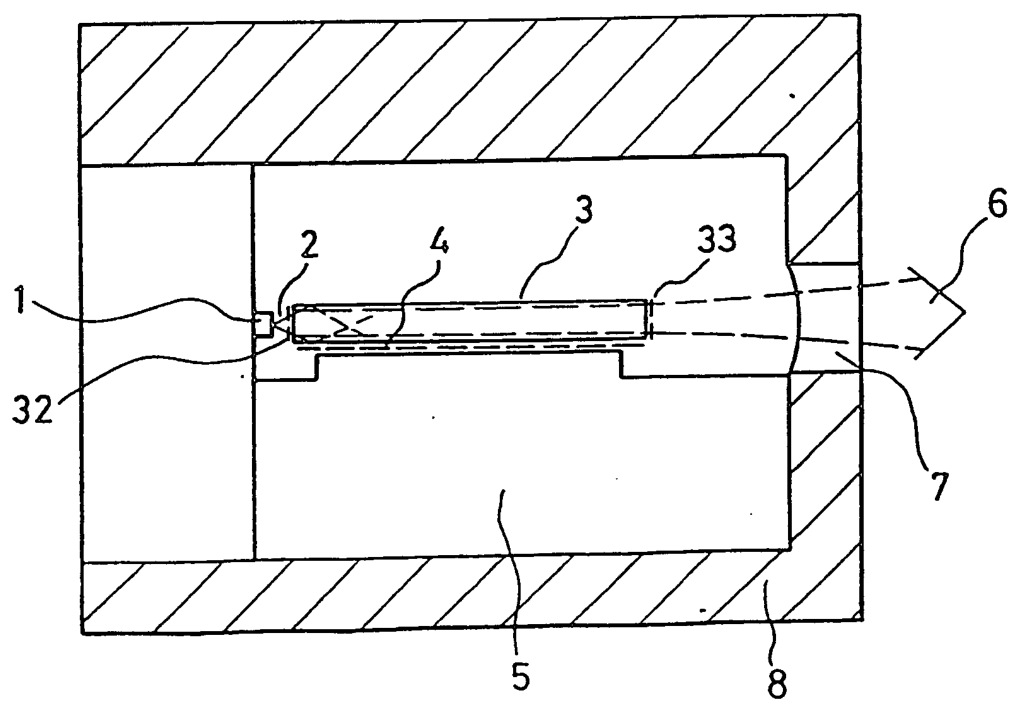


FIG. 21

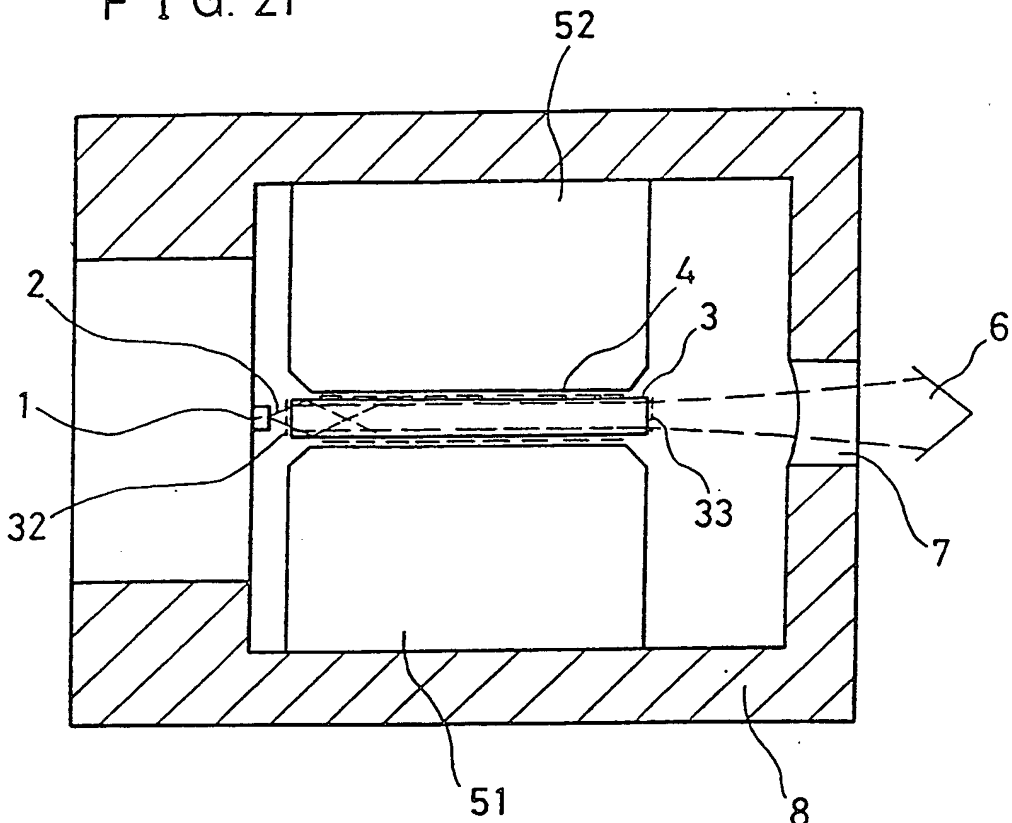
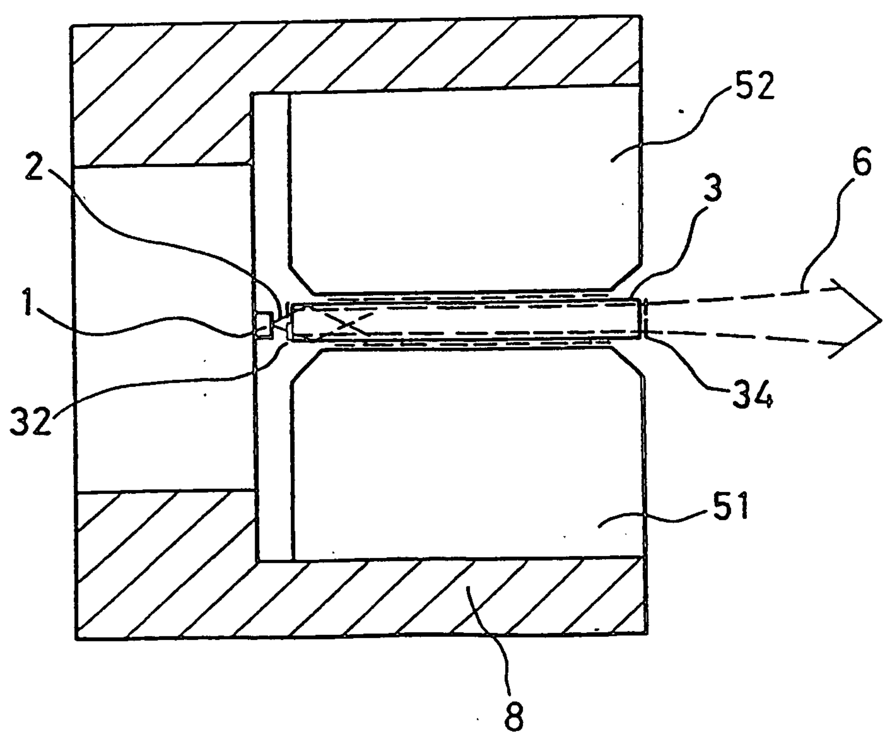
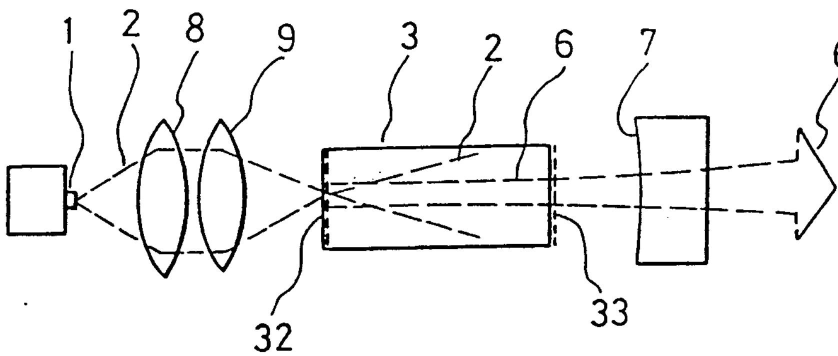


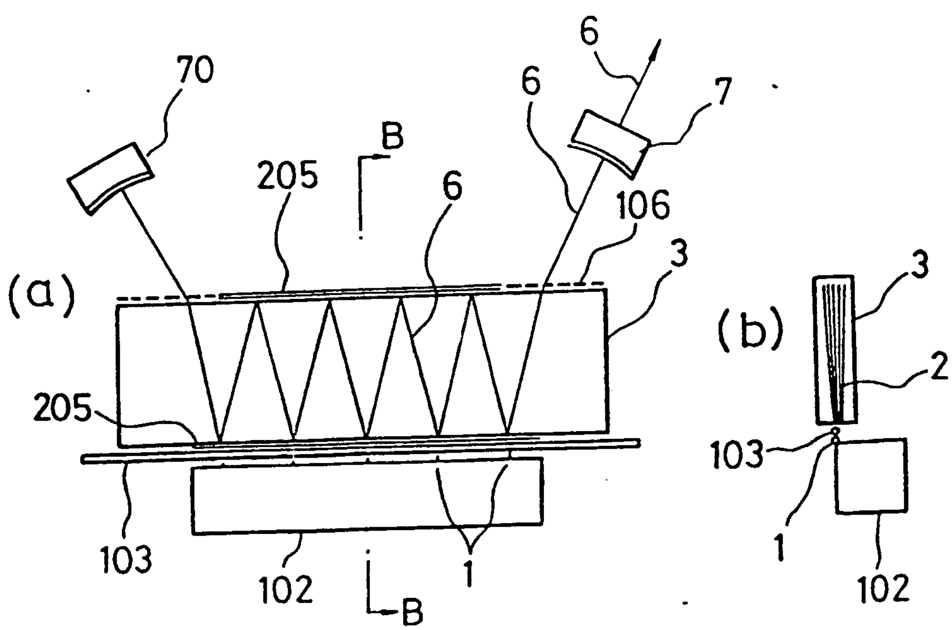
FIG. 22



F I G. 23 (PRIOR ART)



F I G. 24 (PRIOR ART)



A Semiconductor-Laser-Pumped, Solid-State Laser

FIELD OF THE INVENTION

The present invention relates to a solid-state laser having a semiconductor laser as a pumping source, and more particularly, to a semiconductor-laser-pumped, solid-state laser that can enhance the oscillation efficiency and the beam mode.

BACKGROUND OF THE INVENTION

Figure 24 shows a prior art semiconductor-laser-pumped, solid-state laser shown in Japanese Patent Laid-open No. Hei. 1-122180. Figure 24(a) shows an entire structure thereof and 24(b) shows a cross-section in line B-B of figure 24(a). In figures 24(a) and 24(b), reference numeral 1 designates a semiconductor laser which emits a pumping light. A heat sink 102 is provided for mounting the pumping laser 1. Numeral 103 designates a linear shaped lens. A solid-state laser medium 3 comprising, for example YAG(Yttrium Aluminium Garnet) crystal is arranged so as to be pumped by the pumping light from the semiconductor laser 1. Numeral 205 designates a film which selectively reflects light and numeral 106 designates a film which totally transmits light. Numerals 70 and 7 designate a totally reflecting mirror and a partially reflecting mirror, respectively. Numeral 2 designates a pumping light and numeral 6 designates a laser light. Hereinafter, the light

emitted from the semiconductor laser is called as pumping light and the light emitted from the solid-state laser medium 3 is called as laser light, for the sake of distinction.

A description is given of the operation hereinafter. The pumping light 2 emitted from the semiconductor laser 1 is narrowed its divergent angle by the linear shaped lens 103 and is incident to the solid-state laser medium 3. To narrow the divergent angle of the light emitted from the semiconductor laser 1 would not lower the pumping density and it is important in view of obtaining a high laser oscillation efficiency as a result of that. The selective reflecting film 205 has such a reflection selectivity that it transmits the pumping light 2 and totally reflects the laser light 6. By constructing the optical path in a zigzag configuration in the solid-state laser medium 3, in the resonator space produced between the totally reflecting mirror 70 and the partially reflecting mirror 7, a laser light 6 as shown in figure 24 is obtained.

Figure 23 shows a schematic construction diagram of a prior art semiconductor-laser-pumped, solid-state laser shown in Mitsubishi Denki Gihoh vol.63, No.4, (1989) pp. 287 to 290. In figure 23, numeral 1 designates a semiconductor laser as a pumping source, numeral 2 designates laser beam emitted from the semiconductor laser 1 and is called as pumping light hereinafter. Numerals 8 and 9 designate lens.

Numeral 3 designates a solid-state laser medium arranged to be pumped by the pumping light. Numeral 6 designates laser light emitted from the solid-state laser medium 3. Numeral 7 designates a partially reflecting mirror. A totally reflecting coating 32 and a non-reflecting coating 33 which respectively totally reflects and partially reflects the laser light 6 are produced on the facets of the solid-state laser medium respectively and thereby a laser resonator is constituted between the totally reflecting coating 32 and the partially reflecting mirror 7.

A description is given of the operation. The pumping light 2 emitted from the semiconductor laser 1 is made parallel by the lens 8 and is concentrated to be incident to the solid-state laser medium 3 by the lens 9. The pumping light 2 is absorbed while broadening in the solid-state laser medium 3 and thereby the solid-state laser medium 3 is excited. A part of energy of the pumping light 2 that is absorbed is output to the outside as laser light 6.

The conventional semiconductor-laser-pumped, solid-state laser is constructed as described above, and has the following drawbacks:

That is, in the semiconductor-laser-pumped, solid-state laser shown in figure 24, when the divergent angle of the pumping light is large, an idle excited light which would not contribute to the laser light increases and the pumping

efficiency is reduced. Here, the divergent angle of the pumping light in the solid-state laser medium largely varies dependent on the relative positional relationship between the semiconductor laser, the linear lens, and the solid-state laser medium and it is difficult to set it to be small stably. In addition, in this semiconductor-laser-pumped, solid-state laser, the positions of the optical axes of laser light and the pumping light are required to be accurately coincided on the selective reflecting film. However, as the pumping light increases, the thermal distribution in the solid-state laser medium and accompanying refractive index distribution arise, thereby resulting in a variation in the laser optical axis and its deviation against the pumping light incident position. In addition, the optical loss at the selective reflecting film is generally large and the total resonator loss increases as the number of turns in the optical axis increases and it was difficult to obtain high output by arranging a plurality of semiconductor lasers in parallel.

In the semiconductor-laser-pumped, solid-state laser device of figure 23, the broadening of pumping light 2 in the solid-state laser medium 3 is large and it was impossible to substantially reduce the cross section of pumping. Therefore, the threshold value of laser oscillation is increased, thereby reducing the energy

efficiency of the laser oscillation. In addition, the laser light 6 includes a lot of higher order modes and it was difficult to obtain beam of fundamental mode which has good light collecting property.

SUMMARY OF THE INVENTION

The present invention is directed to solving the above-described objects and has for its object of provide a semiconductor-laser-pumped, solid-state laser that can enhance the energy efficiency of laser oscillation and can obtain a stable laser operation.

Other objects and advantages of the present invention will become apparent from the detailed description given hereinafter; it should be understood, however, that the detailed description and specific embodiment are given by way of illustration only, since various changes and modifications within the spirit and scope of the invention will become apparent to those skilled in the art from this detailed description.

In accordance with a first aspect of the present invention, a solid-state laser medium is of a thin flat plate shaped, a rectangular, or a fine circular cross-section, and a semiconductor pumping laser is arranged in close to the facet of the solid-state laser medium. The pumping light is incident to the solid-state laser medium from the facet thereof and the laser resonator is of a

stable type or a waveguide type, having an optical axis coinciding with that of the pumping light. Therefore, the pumping light is confined in a narrow region by the internal reflection of the solid-state laser medium having such as narrower thickness and width than the broadening width of pumping light and is absorbed therein, whereby the energy efficiency of laser oscillation can be enhanced.

In accordance with a second aspect of the present invention, a solid-state laser medium is of a thin flat plate shaped and a semiconductor pumping laser is arranged in close to the side face of the solid-state laser medium. The pumping light is incident to the solid-state laser medium from the side face thereof and the laser resonator is of a stable type or a one-dimensional unstable type, having an optical axis vertical to that of the pumping light. Therefore, by setting the optical axis of the pumping laser in the lengthwise direction of the medium, the region where the optical axis passes through, is broadened throughout the medium, whereby even if the positional relationship between the pumping light and the laser light is deviated, a stable operation is possible.

In accordance with a third aspect of the present invention, a solid-state laser medium is made of a thin flat plate shaped, a rectangular, or a fine circular cross-section and the solid-state laser medium is integrated with

a holding substance and optically polished. Therefore, a surface having the most appropriate curvature can be easily produced and a high efficiency and high beam quality laser is realized.

In accordance with a fourth aspect of the present invention, a solid-state laser medium is of a thin flat plate shaped, a rectangular, or a fine circular cross-section and the solid-state laser medium is fixed to a metal block by optical adhesive. Therefore, the cooling of solid-state laser medium and the mounting with other parts such as the pumping laser diode and output mirror are eased and a high efficiency and high beam quality solid-state laser is obtained.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a diagram showing a semiconductor-laser-pumped, solid-state laser in accordance with a first embodiment of the present invention;

Figures 2 and 3 are diagrams showing a semiconductor-laser-pumped, solid-state laser in accordance with a second and a third embodiments of the present invention, respectively;

Figure 4 is a diagram showing a semiconductor-laser-pumped, solid-state laser in accordance with a fourth embodiment of the present invention;

Figure 5 is a diagram showing a cross-section in line I

- II of figure 4;

Figure 6 is a cross-sectional view showing a fifth embodiment of the present invention;

Figures 7 and 8 are diagrams showing a semiconductor-laser-pumped, solid-state laser in accordance with a sixth and a seventh embodiments of the present invention,respectively;

Figures 9(a) and 9(b) are a vertical and a transverse cross-sectional construction diagrams showing a semiconductor-laser-pumped, solid-state laser in accordance with an eighth embodiment of the present invention;

Figures 10 and 11 are vertical cross-sectional construction diagrams showing a semiconductor-laser-pumped, solid-state laser in accordance with a ninth and tenth embodiments of the present invention, respectively;

Figures 12, 13, and 14 are transverse cross-sectional construction diagrams showing a semiconductor-laser-pumped, solid-state laser in accordance with an eleventh, twelfth, and thirteenth embodiments of the present invention, respectively;

Figures 15(a) to 15(d) are diagrams showing the production steps of a holding substance of the embodiment shown in figure 14;

Figure 16 is a diagram showing a semiconductor-laser-pumped, solid-state laser in accordance with a fourteenth

embodiment of the present invention;

Figure 17 is a diagram showing a semiconductor-laser-pumped, solid-state laser in accordance with a fifteenth embodiment of the present invention;

Figures 18, 19, 20, 21, and 22 are diagrams showing a semiconductor-laser-pumped, solid-state laser in accordance with a sixteenth, seventeenth, eighteenth, nineteenth, and twentieth embodiments of the present invention, respectively;

Figure 23 is a diagram showing a structure of a prior art semiconductor-laser-pumped, solid-state laser; and

Figure 24 is a diagram showing a structure of another prior art semiconductor-laser-pumped, solid-state laser.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Embodiments of the present invention will be described in detail with reference to the drawings.

Figure 1 is a diagram showing a semiconductor-laser-pumped, solid-state laser in accordance with a first embodiment of the present invention. Figure 1(a) is a perspective view from upper and figure 1(b) is a transverse cross-sectional view. In figure 1, the same reference numerals as those in figures 23, 24 are used for the same or corresponding portions. Reference numeral 50 designates a selective reflecting film and a stable type resonator is constituted by this selective reflecting film 50 and the

partially reflecting mirror 7. Reference numeral 41 designates a base block for mounting the solid-state laser medium 3 and a reflecting film 42 is on the base block 41 at between the base block 41 and the solid-state laser medium 3.

The pumping light 2 emitted from the semiconductor laser 1 generally has a large divergence angle such as 60° in the vertical direction and 20° in the horizontal direction of the active layer in full angle and further it has an anisotropy. Here, the pumping laser 1 is arranged such that the direction of larger divergence angle of the laser 1 is the thickness direction of the solid-state laser medium 3.

A description is given of the operation hereinafter. The pumping light 2 of the semiconductor laser 1 is incident to the laser medium 3 arranged close thereto. The introduced light 2 is absorbed while transmitted in a divergent angle which is in accordance with the refractive index difference and the outside portions among the broadened pumping light 2 are reflected by the reflecting film 42 to be again confined in the solid-state laser medium 3. Thus the pumping light 2 is effectively absorbed. The thickness of the solid-state laser medium 3 is small with relative to the broadening width of the pumping light 2 in the solid-state laser medium 3, thereby preventing the

region of pumping light from becoming eminently large with relative to the region of the laser light 6. Therefore, the energy efficiency of laser oscillation is high. An oscillation experiment is carried out using the apparatus of figure 1 and it was possible to obtain as a measured value a YAG output of 200 mW for the pumping laser output 730 mW. This means that it was possible to enhance the oscillation efficiency with relative to that the semiconductor laser output of 1 W is required for obtaining YAG output 200 mW in the prior art lens focusing type device.

In this first embodiment, since the region where the laser light passes is broadened throughout the medium, the positional relationship between the pumping light 2 and the laser beam 6 is not required to be highly precise. That is, the arrangement precision of the pumping laser 1 and the solid-state laser medium 3 is only required to such an extent that they are mounted at predetermine positions on the base block 41 in a range of mechanical precision.

In the first embodiment a reflecting film 42 is provided only at the lower surface of the laser medium 3, but a reflecting film can be also provided at the upper surface of the laser medium 3 as is required. However, when the divergent angle of the pumping light 2 is not so large, the reflecting film 42 can be dispensed with because the pumping light 2 is totally reflected by the side face of the

medium even when the refractive index difference between the laser medium 3 and the outside is not so large.

In addition, it is also possible to adhere a lens to the incident facet of the laser medium 3, whereby the pumping light 2 can be confined in the solid-state laser medium 3 and absorbed therein in further better manner.

Figure 2 shows a second embodiment of the present invention. In this embodiment upper and lower high dielectric constant guides 43 are arranged to put between the solid-state laser medium 3. For example, a metal is used for the high dielectric constant guides 43. Therefore, a waveguide resonator is produced in the plane of thickness direction of the solid-state laser medium 3 between the selective reflecting film 50 and the partially reflecting mirror 7.

Figure 3 shows a third embodiment of the present invention. The width of the solid-state laser medium 3 is also thin in the width direction vertical to the thickness direction and this construction makes the pumping light 2 confined in a narrower region. In this case, the cross-sectional configuration of the solid-state laser medium 3 can be any of rectangular, polygonal, or circular shape and almost the same effects are obtained in any of them.

Figure 4 is a schematic diagram showing a semiconductor-laser-pumped, solid-state laser in accordance

with a fourth embodiment of the present invention and figure 5 is an enlarged view of cross-section at line I - II of figure 4. In these figures, numeral 41 designates a base block and numerals 42 and 45 designate reflecting films. Totally reflecting mirrors 70 and 71 and a partially reflecting mirror 7 constitute a stable type resonator together with the solid-state laser medium.

A description is given of the operation. The pumping light 2 of the semiconductor laser 1 has a large divergent angle such as 60° in the vertical direction and 20° in the horizontal direction of the active layer and has an anisotropy in the broadening. Therefore, the pumping light 2 incident to the laser medium 3 arranged in close to the semiconductor laser 1 is transmitted while a part thereof is absorbed in a large divergent angle in accordance with the refractive index difference and the outside portions of the broadened pumping light 2 are reflected by the reflecting film 42 to be confined in the laser medium 3. Therefore, the pumping light is effectively absorbed. The thickness of the solid-state laser medium 3 is produced thin with relative to the broadening width of the pumping light 2 in the solid-state laser medium 3 and the laser beam 6 fills with the almost entire region of the cross-section of the solid-state laser medium 3 and the pumping region is prevented from becoming eminently large with relative to the

laser beam region. Therefore, the energy efficiency of the laser oscillation is high. In addition, the positional relationship between the pumping light 2 and the laser beam 6 is not required to be highly precise and the parallel arrangement of a plurality of pumping lasers 1 can be constructed such that the solid-state laser medium 3 and the pumping lasers 1 are mounted at predetermined positions on the base block 41 within a range of mechanical precision.

In the above-described fourth embodiment, reflecting films 42 are provided at the lower and the upper surfaces of the solid-state laser medium 3, but in a case where the divergent angle of the pumping light 2 is not so large, the pumping light 2 is totally reflected by the side faces of the medium 3 even when the refractive index difference between the laser medium 3 and the outside is not so large. Therefore, the reflecting film 42 can be dispensed with.

Figure 6 shows an enlarged view in cross-section of a fifth embodiment of the present invention. In this alternative embodiment a lens 43 is adhered to the solid-state laser medium 3 and thereby the pumping light 2 is confined and absorbed in a further better manner in the solid-state laser medium 3.

Figure 7 is a diagram showing a sixth embodiment in accordance with the present invention. In figure 7, reference numeral 72 designates a totally reflecting film

which is directly coated onto the facet of the solid-state laser medium 3. In this embodiment, by providing totally reflecting films 72 directly on the facet of the solid-state laser medium 3 by coating, the totally reflecting mirror 71 can be dispensed with, whereby the resonator is simplified.

Figure 8 is a diagram showing a seventh embodiment of the present invention. In figure 8, numeral 170 designates a collimating mirror and numeral 180 designates an enlarging mirror. In this embodiment, as a laser resonator a one-dimensional unstable type resonator constituted by the collimating mirror 170 and the enlarging mirror 180 is constituted in the plane parallel with the surfaces of the flat plate shaped solid-state laser medium 3 and a stable type resonator or a waveguide type resonator in the plane vertical to the above-described plane are constituted.

Figures 9(a) and 9(b) show a vertical cross-sectional structure and a transverse cross-sectional structure in accordance with an eighth embodiment of the present invention, respectively. In figure 9, numeral 1 designates a semiconductor pumping laser which generates an pumping light 2. Numeral 3 designates a solid-state laser medium having a thickness and width less than the broadening width of the pumping light and comprising such as Nd:YAG ($Y_{3-x}Nd_xAl_5O_{12}$) crystal of having a length of 10 mm and of square cross-section of one-dimension of 0.3 mm. A

reflection coating 31 is executed to the side faces of the Nd:YAG crystal to reflect the pumping light 2. Numeral 4 designates an adhesive and numeral 105 designates a holding substance comprising for example glass or YAG crystal and this has for example length of 10 mm and diameter of 3 mm. Numeral 32 designates a first coating executed to the facet of the solid-state semiconductor laser medium 3 and this is non-reflecting against the pumping light 2 and totally reflecting against the laser light 6. Numeral 33 is a second coating executed to the facet of the solid-state laser medium 3 and this is of high reflectance against the pumping light 2 and non-reflecting against the laser light 6. Numeral 7 designates a partially reflecting mirror. Here, the solid-state laser medium 3 and the holding substance 105 are integrated by the adhesive 4 and they are in appropriate states for the processing. Therefore, an optical element constituting a laser resonator can be produced at high precision and easily by optically polishing the facet and executing coating to the facet. Here, the pumping light 2 emitted from the semiconductor laser 1 has generally large broadening and for example the divergence angle in full angle has an angle of 60° in the vertical direction and an angle of 20° in the horizontal direction of the active layer of the semiconductor laser 1 and has an anisotropy. Thus, in this embodiment the semiconductor

pumping laser 1 and the solid-state laser medium 3 are arranged closely to each other and the facet of solid-state laser medium 3 is arranged in the vicinity of a point where the beam radius of the pumping light amounts to the minimum, whereby the pumping light 2 is effectively introduced into the solid-state laser medium 3.

A description is given of the production method.

Generally, when a hard material such as YAG crystal is a bar shaped one having a small cross-section, it is quite difficult to produce curvatures required for a laser resonator at the facet. In this embodiment, the YAG crystal is cut out as a square long bar type and these are buried in and adhered to the holding substance and the holding substance including the YAG crystal rectangular long bar is cut at a desired length and the facets are polished and further a coating is executed to the facets as required. Therefore, the processing of the solid-state laser medium can be performed easily and at high precision.

A description is given of the operation.

The pumping light 2 is incident from the facet of the solid-state laser medium 3 to which a coating 32 is executed and the introduced pumping light 2 repeats internal reflections at the reflecting coating 31 which is executed to the side face of the solid-state laser medium 3. The pumping light 2 is absorbed in the solid-state laser medium

3 while repeating reflections therein and it effectively excites the laser medium 3 with keeping being confined therein. In this embodiment the cross-section of the solid-state laser medium 3 is small with relative to the natural broadening of the pumping light 2 and the pumping region is prevented from becoming eminently large with relative to the region of the laser light. In the solid-state laser of figure 9, a stable type resonator is constituted between the coating 32 of the laser medium 3 and the partial reflecting mirror 7 and when the curvature radii of the coating 32 and the partial reflecting mirror 7 are 400 mm and the resonator length 10 mm, the beam diameter of the fundamental mode that is Gaussian mode is about 0.3 mm. Therefore, the fundamental mode cross-section of the laser and the cross-section in which the pumping light is confined coincide with each other and a high quality Gaussian beam can be output at high efficiency.

Here, the reflection coating 31 at the side face of the solid-state laser medium 3 can be dispensed with if circumstances allow.

While in the above-described eighth embodiment, the semiconductor laser 1 is arranged closely to the solid-state laser medium 3 and the pumping light 2 is directly incident to the solid-state laser medium, the pumping light 2 can be incident to the solid-state laser medium 3 after the

divergent angle of the pumping light 2 is modified by the lens systems 8 and 9 as shown in the ninth embodiment of figure 10.

Furthermore, by processing the solid-state laser medium together with the holding substance with burying the laser medium in and adhering the same to the holding substance, the curved plane at the facet of the solid-state laser medium can be produced precisely, and this makes it possible to produce the partially reflecting mirror 7 in the embodiment of figure 9 at the facet of the solid-state laser medium 3.

Figure 11 shows a tenth embodiment of the present invention in which a partially reflecting mirror is produced at the facet of the solid-state laser medium. In figure 11 numeral 34 designates a coating having a partial reflectivity against the laser light 6 produced at the rear facet of the solid-state laser medium 3. In this embodiment, a laser resonator is constituted by the both facets of the solid-state laser medium 3 and quite a simple and substantial resonator can be obtained.

In the above-illustrated eighth to tenth embodiments, the configuration of the holding substance 105 and the solid-state laser medium 3 are not limited to those described above, and various modifications in the configuration thereof is possible in accordance with such as

resonator structures.

Figure 12 shows a cross-sectional structure of a solid-state laser in accordance with an eleventh embodiment of the present invention. In this embodiment, a circular laser medium 3 having a diameter less than the broadening width of the pumping light in the solid-state laser medium is inserted in the holding substance 105 which has a circular hole and adhered and fixed thereto.

Figure 13 shows a cross-sectional structure of a solid-state laser in accordance with a twelfth embodiment of the present invention. This embodiment utilizes plate-shaped solid-state laser medium 3 which has a thickness less than the broadening width of the pumping light in the solid-state laser medium and has a rectangular cross-section. In this embodiment, the semiconductor laser 1 and the solid-state laser medium 3 are arranged such that the direction in which the broadening of pumping light 2 emitted from the semiconductor laser 1 is large and the thickness direction of the solid-state laser medium 3, that is, the direction of the short edge of the rectangular medium 3 coincide with each other and almost the same effects as the ninth embodiment are obtained.

Figure 14 is a diagram showing a cross-sectional structure of a solid-state laser in accordance with a thirteenth embodiment of the present invention. In this

embodiment, the solid-state laser medium 3 which has a thickness and width less than the broadening width of the pumping light in the solid-state laser medium and has a rectangular cross-section and bar-shaped configuration is adhered and fixed in the holding substance 105 having a rectangular hole. Generally, it is difficult to produce a rectangular hole at high precision, but according to the processes shown in figures 15(a) to 15(d), the holding substance 105 as similar as that of figure 14 can be easily and precisely produced. That is, first of all, as shown in figure 15(a), two holding substances 51 and 52 and the solid-state laser medium 3 are adhered by adhesive 4. Then, after the side face 55 is polished together with the solid-state laser medium 3, it is adhered to the holding substance 53 by the adhesive 4 as shown in figure 5(b), and further the side face 56 is polished together with the solid-state laser medium 3, and thereafter, it is adhered to the holding substance 54 by adhesive 4 as shown in figure 5(c) and a configuration shown in figure 15(b) is obtained.

Figure 16 shows a fourteenth embodiment of the present invention. In this embodiment the optical axis of the laser resonator and the optical path of the pumping light cross vertical to each other. Figures 16(a) and 16(b) show vertical cross-sections and figure 16(c) shows a transverse cross-section. In figure 16, the holding substance 105 is

constituted by metal or non-metal having good thermal conductivity and it is integrated with the solid-state laser medium 3 and further it is polished to constitute a one-dimensional unstable type resonator (in the embodiment negative-branch co-focal point unstable type) and totally reflecting coating 35 and non-reflection coating 36 are executed to the facets thereof. In this embodiment, a laser resonator is constituted by the both facets of the solid-state laser medium and similarly as in the embodiment of figure 11, quite a simple and substantial resonator is obtained.

Figure 17 shows a schematic construction of a semiconductor-laser-pumped, solid-state laser in accordance with a fifteenth embodiment of the present invention. In figure 17, reference numeral 1 designates a semiconductor laser generating a pumping light. Numeral 3 is a solid-state laser medium comprising such as Nd:YAG($Y_{3-x}Nd_xAl_5O_{12}$) crystal of rectangular cross-section having a length of 5 mm, width of 2 mm, and thickness of 0.5 mm. Numeral 4 designates optical adhesive. Numeral 5 designates a metal block, for example a copper block on which gold gilding is executed which has a rectangular parallelepiped configuration of length of 5 mm, width of 4 mm, and thickness of 3 mm. Numeral 32 designates a coating produced at the facet of the solid-state laser medium 3 which is non-

reflecting against the pumping light 2 and is totally reflecting against the laser light 6. Numeral 33 designates an optical thin film produced at the facet of the solid-state laser medium 3 and it is highly reflecting against the pumping light 2 and is non-reflecting against the laser light 6. Numeral 7 designates a partially reflecting mirror and numeral 8 designates a container.

The pumping light 2 emitted from the semiconductor laser 1 has generally large broadening and the divergent angle in full angle thereof is quite large to be 60° in the vertical direction and 20° in the horizontal direction of the active layer of the semiconductor laser 1, and also has an anisotropy. However, by arranging the semiconductor laser 1 and the solid-state laser medium 3 in close to each other, the pumping light 2 can be effectively introduced into the laser medium 3.

A description is given of the operation. The pumping light 2 is incident to the facet of the solid-state laser medium 3 on which coating 32 is executed. The refractive index of the solid-state laser medium 3 is about 1.83 in case where it is Nd:YAG crystal laser. When an adhesive which has refractive index close to 1.5 such as silpot, No. 184 of Dow Cohning Co., is used as the optical adhesive 4, it is possible to produce a totally reflecting condition against the pumping light 2 between the solid-state laser

medium 3 and the optical adhesive 4. On the other hand, it is possible to produce a totally reflecting condition against the further wide incident angle at the non-adhering plane, that is, the upper surface of the solid-state laser medium by the interface between the solid-state laser medium 3 and air. Therefore, the incident pumping light repeats internal reflection at the upper and lower surfaces 31 of the solid-state laser medium 3 and is absorbed in the solid-state laser medium 3 and effectively excites the laser medium with keeping being confined therein. The light pumping region in the semiconductor laser medium can be made about 0.5 mm in both vertical and horizontal directions.

The heat generated in the solid-state laser medium 3 is efficiently radiated through the metal block 5 and the container 8.

In this embodiment, a stable type resonator is constituted between the coating 32 and the partially reflecting mirror 7. When the coating 32 is a plane coating and the curvature radius of partially reflecting mirror is 2500 mm and the resonator length 10 mm, the beam diameter of the fundamental mode (Gaussian mode) is about 0.35 mm. Therefore, the cross-section of the fundamental mode and the cross-section to which the pumping light is confined of the laser coincide with each other and a high quality Gaussian beam can be output at high efficiency.

Figure 18 shows a sixteenth embodiment of the present invention where the corner edges of the metal block 5 which are adjacent to the facet of the solid-state laser medium 3 are cut down. By adopting this construction, it is possible to prevent the optical adhesive 4 from bonding to the facet of the solid-state laser medium 3 in the adhesion.

Figure 19 shows a seventeenth embodiment of the present invention in which the length of the metal block 5 is made slightly less than the length of the solid-state laser medium 3. Also in this configuration, the optical adhesive 4 can be prevented from bonding to the facet of the solid-state laser medium 3.

Figure 20 shows an eighteenth embodiment of the present invention in which the metal block 5 is provided with a step. In this embodiment the optical adhesive 4 can be prevented from bonding to the facet of the solid-state laser medium 3 and the integration with the semiconductor laser 1 and the partially reflecting mirror 7 is eased and a substantial resonator is obtained.

In the above-illustrated fifteenth to eighteenth embodiments a metal block 5 is adhered only to one side surface of the solid-state laser medium 3. However, as shown in a nineteenth embodiment of the present invention shown in figure 21, the metal blocks 51 and 52 can be adhered to the both of lower and upper surfaces of solid-

state laser medium 3, respectively. By this construction, the cooling of solid-state laser medium 3 is further improved.

In the above-illustrated embodiment a stable type resonator is constituted between the coating 32 and the partially reflecting mirror 7. However, a partially reflecting mirror can be produced at the facet of the solid-state laser medium 3 as in the twentieth embodiment of the present invention shown in figure 22. In figure 22, reference numeral 34 designates a partially reflecting coating against the laser light 6 provided at the rear facet of the solid-state laser medium. In this case, a laser resonator is constituted by the both facets of solid-state laser medium 3 and quite a simple and substantial resonator is obtained.

In the above-illustrated fifteenth to twentieth embodiments the facet pumping type semiconductor-laser-pumped, solid-state laser in which the optical axis of the pumping light 2 from the semiconductor laser 1 and the optical axis of the laser light 6 coincide with each other are described. However, also in the side face pumping type semiconductor-laser-pumped, solid-state laser in which optical axes of the pumping light 2 and the laser light 6 cross vertically, the laser device can be constituted such that the solid-state laser medium is fixed to a metal block

by optical adhesive. Thus, a solid-state laser which is easy in mounting other parts such as a semiconductor pumping laser and output mirror and is superior in the cooling effect can be obtained.

As is evident from the foregoing description, a solid-state laser medium is of a thin flat plate shaped, a rectangular having a thinner thickness and width than the broadening angle of the pumping light in the laser medium, or a circular cross-section of fine diameter less than the broadening angle of the pumping light in the laser medium, and a semiconductor pumping laser is arranged in close to the facet of the solid-state laser medium. The pumping light is incident from the facet of the medium and the laser resonator is made of a stable type or a waveguide type that has an optical axis in the length direction of the medium, that is, that has an optical axis coinciding with the transmission direction of the pumping light. Therefore, the pumping light is confined in a narrow region while repeating internal reflections in the solid-state laser medium that has narrow thickness and narrow width than the broadening width of the pumping light and is absorbed therein, thereby the energy efficiency of laser oscillation is enhanced.

In accordance with a second aspect of the present invention, the solid-state laser medium is of a thin flat plate shaped and plural semiconductor lasers are arranged in

close to the side face of the solid-state laser medium, and the pumping light is incident from the side face of the medium and the laser resonator is made of a stable type or a one-dimensional unstable type that has an optical axis in the length direction of the medium, that is, that has an optical axis vertical to the pumping light. Therefore, the region where the optical axis passes through is broadened throughout the medium, whereby even if the positional relationship between the pumping light and the laser light is deviated, a stable operation is obtained.

In accordance with a third aspect of the present invention, a solid-state laser medium is of a thin flat plate shaped, a rectangular having a thinner thickness and width than the broadening angle of the pumping light in the laser medium, or a circular cross-section of fine diameter less than the broadening angle of the pumping light in the laser medium, and the facet of the solid-state laser medium is optically polished after integrating the laser medium with a holding substance having a large cross-section. Therefore, the surface having the most appropriate curvature for the laser oscillation can be easily produced and an efficient and a high beam quality laser is realized.

In accordance with a fourth aspect of the present invention, a solid-state laser medium is of a thin flat plate shaped, a rectangular having a thinner thickness and

width than the broadening angle of the pumping light in the laser medium, and the solid-state laser medium is fixed to a metal block by optical adhesive. Therefore, the cooling of solid-state laser medium and mounting of other parts such as laser diode or output mirror are eased and an efficient and a high beam quality solid-state laser is obtained.

WHAT IS CLAIMED IS:

1. A semiconductor-laser-pumped, solid-state laser comprising:

a semiconductor laser for emitting pumping light;

a solid-state laser medium arranged to be excited by said pumping light;

a laser resonator structure for emitting laser light from said solid-state laser medium;

said solid-state laser medium being of plate shaped having a thickness less than the broadening width of said pumping light in said solid-state laser medium;

said semiconductor laser being arranged in close to the facet of said solid-state laser medium; and

said laser resonator structure having such a construction that the optical axis thereof coincides with the optical axis of said pumping light.

2. A semiconductor-laser-pumped, solid-state laser as defined in claim 1, wherein said laser resonator structure is a stable type.

3. A semiconductor-laser-pumped, solid-state laser as defined in claim 2, wherein a selective reflecting film which transmits said pumping light and totally reflects said laser light is disposed on said facet of said solid-state

laser medium.

4. A semiconductor-laser-pumped, solid-state laser as defined in claim 3, wherein a partially reflecting mirror is disposed opposite to the other facet of said solid-state laser medium so as to constitute said stable type resonator between said partially reflecting mirror and said selective reflecting film.

5. A semiconductor-laser-pumped, solid-state laser as defined in claim 1, wherein high dielectric constant guides are disposed on both surfaces of said solid-state laser medium thereby to produce a waveguide resonator in said solid-state laser medium.

6. A semiconductor-laser-pumped, solid-state laser comprising:

a semiconductor laser for emitting pumping light;

a solid-state laser medium arranged to be excited by said pumping light;

a laser resonator structure for emitting laser light from said solid-state laser medium;

said solid-state laser medium being of rectangular cross-section having a thickness and a width less than the broadening width of said pumping light in said solid-state

laser medium;

said semiconductor laser disposed in close to the facet of said solid-state laser medium; and

said laser resonator structure having such a construction that the optical axis thereof coincides with that of said pumping light.

7. A semiconductor-laser-pumped, solid-state laser as defined in claim 6, wherein said laser resonator structure is a stable type.

8. A semiconductor-laser-pumped, solid-state laser as defined in claim 7, wherein a selective reflecting film which transmits said pumping light and totally reflects said laser light is disposed on said facet of said solid-state laser medium.

9. A semiconductor-laser-pumped, solid-state laser as defined in claim 8, wherein a partial reflecting mirror is disposed opposite to the other facet of said solid-state laser medium so as to constitute said stable type resonator between said partially reflecting mirror and said selective reflecting film.

10. A semiconductor-laser-pumped, solid-state laser

comprising:

a semiconductor laser for emitting pumping light;

a solid-state laser medium arranged to be excited by said pumping light;

a laser resonator structure for emitting laser light from said solid-state laser medium;

said solid-state laser medium being of circular cross-section having a diameter less than the broadening width of said pumping light in said solid-state laser medium;

said semiconductor laser disposed in close to the facet of said solid-state laser medium; and

said laser resonator structure having such a construction that the optical axis thereof coincides with that of said pumping light.

11. A semiconductor-laser-pumped, solid-state laser as defined in claim 10, wherein said laser resonator structure is a stable type.

12. A semiconductor-laser-pumped, solid-state laser as defined in claim 11, wherein a selective reflecting film which transmits said pumping light and totally reflects said laser light is disposed on said facet of said solid-state laser medium.

13. A semiconductor-laser-pumped, solid-state laser as defined in claim 12, wherein a partially reflecting mirror is disposed opposite to the other facet of said solid-state laser medium so as to constitute said stable type resonator between said partial reflecting mirror and said selective reflecting film.

14. A semiconductor-laser-pumped, solid-state laser comprising:

a semiconductor laser for emitting pumping light;

a solid-state laser medium arranged to be excited by said pumping light;

a laser resonator structure for emitting laser light from said solid-state laser medium;

said solid-state laser medium being of plate shaped having a thickness less than the broadening width of said pumping light in said solid-state laser medium;

said semiconductor laser being arranged in plural in parallel in close to the side face of said solid-state laser medium; and

said laser resonator structure having such a construction that the optical axis thereof crosses vertically with that of said pumping light.

15. A semiconductor-laser-pumped, solid-state laser as defined in claim 14, said resonator structure is a stable type.

16. A semiconductor-laser-pumped, solid-state laser as defined in claim 14, wherein one dimensional unstable type resonator is constituted by a collimating mirror and an enlarging mirror in the plane parallel with the surface of said flat plate shaped solid-state laser medium.

17. A semiconductor-laser-pumped, solid-state laser as defined in claim 16, wherein a stable type resonator is constituted in the plane vertical to the surface of said flat plate shaped solid-state laser medium.

18. A semiconductor-laser-pumped, solid-state laser as defined in claim 16, wherein a waveguide type resonator is constituted in the plane vertical to the surface of said flat plate shaped solid-state laser medium.

19. A semiconductor-laser-pumped, solid-state laser as defined in claim 14, wherein a lens is adhered to said side face of said solid-state laser medium so that said pumping light is directly incident to said solid-state laser medium.

20. A semiconductor-laser-pumped, solid-state laser comprising:

a semiconductor laser for emitting pumping light;

a solid-state laser medium arranged to be excited by said pumping light;

a laser resonator structure for emitting laser light from said solid-state laser medium;

said solid-state laser medium being arranged in the vicinity of a point where the beam radius of said pumping light amounts to the minimum, being of plate shaped having a thickness less than the broadening width of said pumping light in said solid-state laser medium; and

said solid-state laser medium being integrated with a holding substance and optically polished.

21. A semiconductor-laser-pumped, solid-state laser as defined in claim 20, wherein said solid-state laser medium comprising YAG crystal and said holding substance comprising glass or YAG crystal.

22. A semiconductor-laser-pumped, solid-state laser as defined in claim 20, wherein said laser resonator structure is constituted by a coating executed to the optically polished facet of said solid-state laser medium and a partially reflecting mirror disposed opposite to the other

facet of said solid-state laser medium.

23. A semiconductor-laser-pumped, solid-state laser as defined in claim 20, wherein said laser resonator is constituted by the both facets of said solid-state laser medium.

24. A semiconductor-laser-pumped, solid-state laser comprising:

a semiconductor laser for emitting pumping light;

a solid-state laser medium arranged to be excited by said pumping light;

a laser resonator structure for emitting laser light from said solid-state laser medium;

said solid-state laser medium being arranged in the vicinity of a point where the beam radius of said pumping light amounts to the minimum, being of rectangular cross-section having a thickness and a width less than the broadening width of said pumping light in said solid-state laser medium; and

said solid-state laser medium being integrated with a holding substance and optically polished.

25. A semiconductor-laser-pumped, solid-state laser as defined in claim 24, wherein said solid-state laser medium

comprising YAG crystal and said holding substance comprising glass or YAG crystal.

26. A semiconductor-laser-pumped, solid-state laser as defined in claim 24, wherein said laser resonator structure is constituted by a coating executed to the optically polished facet of said solid-state laser medium and a partially reflecting mirror disposed opposite to the other facet of said solid-state laser medium.

27. A semiconductor-laser-pumped, solid-state laser as defined in claim 24, wherein said laser resonator is constituted by the both facets of said solid-state laser medium.

28. A semiconductor-laser-pumped, solid-state laser comprising:

a semiconductor laser for emitting pumping light;

a solid-state laser medium arranged to be excited by said pumping light;

a laser resonator structure for emitting laser light from said solid-state laser medium;

said solid-state laser medium being arranged in the vicinity of a point where the beam radius of said pumping light amounts to the minimum, being of circular cross-

section having a diameter less than the broadening width of said pumping light in said solid-state laser medium; and

said solid-state laser medium being integrated with a holding substance and optically polished.

29. A semiconductor-laser-pumped, solid-state laser as defined in claim 28, wherein said solid-state laser medium comprising YAG crystal and said holding substance comprising glass or YAG crystal.

30. A semiconductor-laser-pumped, solid-state laser as defined in claim 28, wherein said laser resonator structure is constituted by a coating executed to the optically polished facet of said solid-state laser medium and a partially reflecting mirror disposed opposite to the other facet of said solid-state laser medium.

31. A semiconductor-laser-pumped, solid-state laser as defined in claim 28, wherein said laser resonator is constituted by the both facets of said solid-state laser medium.

32. A semiconductor-laser-pumped, solid-state laser comprising:

a semiconductor laser emitting pumping light;

a solid-state laser medium arranged to be excited by said pumping light, having a sufficiently thin cross-section against the broadening of said pumping light;

a laser resonator structure for emitting laser light from said solid-state laser medium;

said solid-state laser medium being fixed to a metal block via optical adhesive.

33. A semiconductor-laser-pumped, solid-state laser as defined in claim 32, wherein said solid-state laser medium comprises YAG crystal and said metal block comprises a copper block on which gold gilding is plated .

34. A semiconductor-laser-pumped, solid-state laser as defined in claim 32, wherein said laser resonator structure is a stable type resonator constituted by a coating and a partially reflecting mirror.

35. A semiconductor-laser-pumped, solid-state laser as defined in claim 32, wherein corner edges of said metal block which are adjacent to the facet of said solid-state laser medium are cut down.

36. A semiconductor-laser-pumped, solid-state laser as defined in claim 32, wherein the length of said metal block

is slightly less than the length of said solid-state laser medium.

37. A semiconductor-laser-pumped, solid-state laser as defined in claim 32, wherein said metal blocks are adhered to the both surfaces of said solid-state laser medium.

38. A semiconductor laser-pumped solid-state laser constructed, adapted and arranged to operate substantially as described hereinbefore with reference to and as shown in figures 1 to 22 of the drawings.

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